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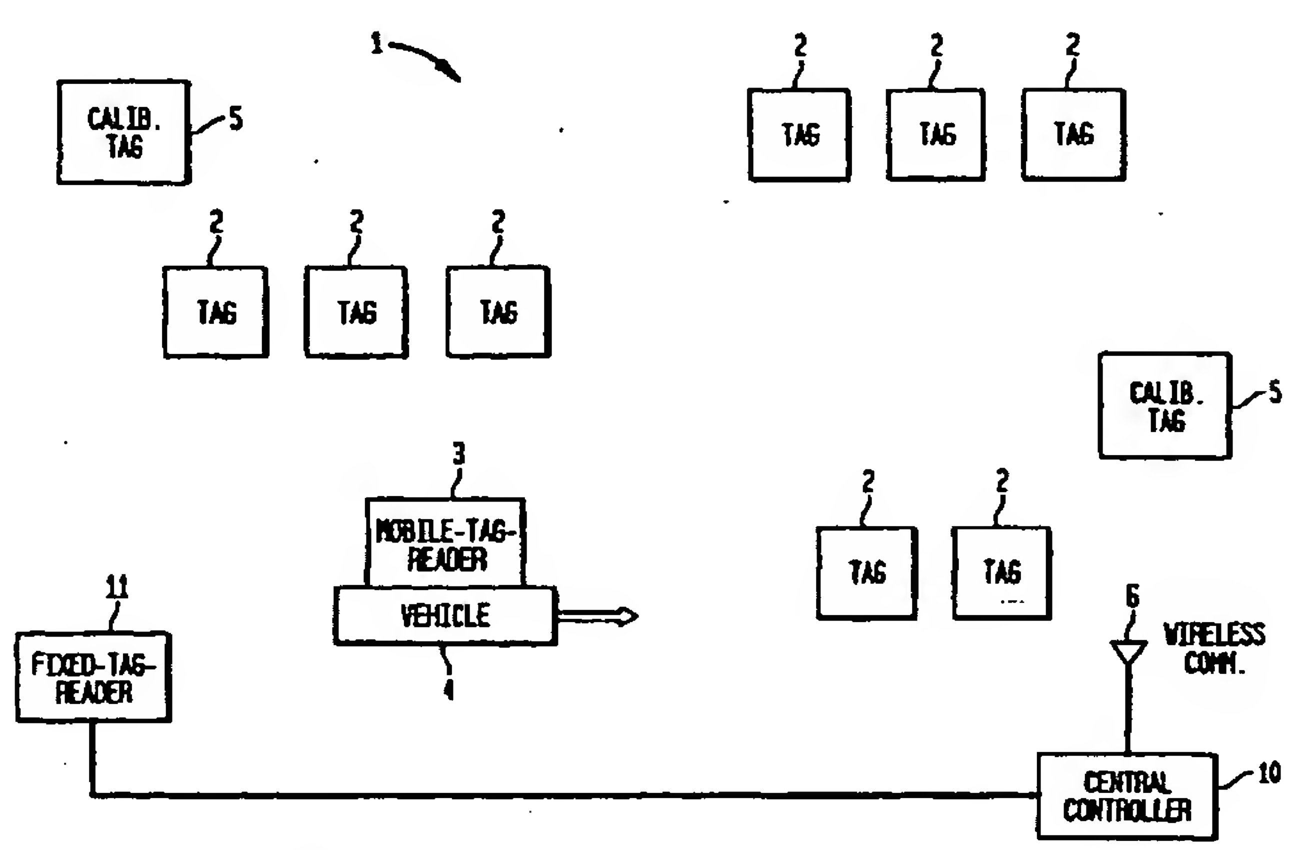
(54) Title: METHOD AND APPARATUS FOR MOBILE TAG READING



(57) Abstract: A mobile tag reader (3) and method for tracking tags (2) for an inventory control and/or security of distributed assets. Radio frequency identification (RFID) tags (2) may be attached to stationary or moveable assets and communicate with one RFID tag readers (3, 11). The communication may provide information to a central or remote controller (10) about the identity, position and/or the status of the tags (2) and assets. The absolute positions of the tagged assets may be determined by the mobile tag reader (3) or central controller (10), and the absolute position of the mobile reader may be ascertained from communications with tags in fixed known locations. Typical applications are for indoor inventory control with the mobile tag readers being mounted to roving trucks, forklifts, or being carried by personnel.

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METHOD AND APPARATUS FOR MOBILE TAG READING

Field of the Invention

The invention relates to location and position identification of mobile and stationary assets, such as items warehoused in a storage facility.

Background of the Invention

Monitoring and tracking the location of assets in a facility can be important, for example, for purposes of inventory and process control. One class of several different solutions that has been used to track assets is a Real Time Locating System (RTLS). This type of system usually includes a set of "interrogator" antennas arranged in an environment which can communicate over radio frequency (RF) bands with "tags" attached to objects, e.g., assets, in the environment which are to be tracked or inventoried. The tags and the antenna transceivers communicate using RF communication bands, and the information gathered from the tags is used by the system to store useful data about the tagged assets in a database and/or to determine the location or the state of the tags. As used herein, the term "position" refers to an actual distance and/or direction of an object relative to another object or reference point. The term "absolute position" refers to a position of an object relative to a fixed geographic reference point, e.g., geographic latitudinal and longitudinal coordinates, a vector defined from a known geographic point, and so on. The term "location" refers more generally to an area in which an object is located with respect to another object or reference point.

Some RTLS's employ Radio Frequency IDentification (RFID) tags, which are available in many forms, both passive and active, but in most cases function as beacons or receiver-transmitter units with ranges from several feet to several hundred feet, depending on a variety of factors, such as power required to operate the tag, cost, and size. The tags are referred to as RFID tags because they commonly encode or modulate the return RF signal with their unique serial identification data so that the system can recognize the individual tags. Other information may be encoded into the tag transmission signal, such as the state of the tag's battery, a tamper condition, or position information generated using a Global Positioning System (GPS). Some examples of

RFID tags in daily use are short range tags for use in automated gas pump payment and automated highway toll collection. Another example is very small, low-power tags embedded under the skin of household pets, used with a national database for identification of lost animals.

A RTLS may or may not use RFID. For example, while a RTLS employing RFID tags and tag readers is, of course, a RFID RTLS, other RTLS's, such as GPS, infrared, and ultrasonic systems are not RFID systems.

An example of a commercially available RTLS used for tracking and identification of assets is the 3D-iD™ Local Positioning System (LPS) from PinPoint Corporation. 3D-iD is a trademark of the PinPoint Corporation. The Firefly™ system from WhereNet Corporation is another example. Firefly is a trademark of WhereNet Corporation. In contrast to a 3D-iD tag, a Firefly tag is not a transponder; rather it emits a beaconing signal that is simultaneously received by a network of readers, and the readers use differential time of arrival of the beaconing signal to estimate tag position. Other systems include the Electronic Home Arrest Monitoring (EHAM) system from B.I., as well as systems from Savi Technology, Inc. These systems may also use UHF beacons, and estimate tag location based on proximity and/or signal strength. Various other RTLS designs have been proposed and/or commercialized, utilizing GPS, E-911, Doppler shift, infrared emitters, ultrasonic emitters, etc.

As an example, one RTLS using infrared and ultrasonic communication channels has been described, and may be used to determine asset location. The system equips moving assets, such as employees, with a transceiver that periodically emits an infrared flash. Fixed calibration emitters receiving the flash emit an ultrasonic signal in a specific sequence that is received by the transceiver. Based on the time between when the infrared flash was output and the time the ultrasonic signal is received from an emitter, the transceiver or other device can determine the position of the asset relative to the fixed emitters.

In some cases, RFID tags cannot be communicated with by fixed antenna transceivers, preventing an asset locating system from determining where some assets are. For example, some RFID tags can suffer from short operating ranges, and are prone to having their communication signals disrupted by attenuating objects in the communication path. Reflections from reflecting objects in the neighborhood of some

RFID tags can also affect their reliability. Thus, a need exists for a more economical, reliable, and flexible system for coverage of extended facilities, and particularly enclosed facilities where the use of Global Positioning System (GPS) is not possible because communication signals from satellites will not penetrate the structures enclosing the facility. In other applications, the use of GPS is not feasible due to the high cost of placing GPS receivers onto all assets to be tracked. Additionally, such systems often consume too much power to be routinely installed on a large number of items that may ideally be tracked for extended periods of time.

Summary of the Invention

An embodiment of the invention provides a mobile tag reader that can be used to communicate with tags that are either fixed in position or attached to assets that are movable. By communicating with the tags, the mobile tag reader can generate information suitable for determining the absolute position of the tag reader and/or the movable tags. The tag reader may store information about the relative position of assets in its vicinity onboard or transmit this information to a central base station computer, or central controller. The relative and/or absolute positions of the tag reader and the tagged assets may be determined using a positioning system onboard the tag reader, such as a GPS or an inertial navigation system, or the positions may be determined subsequently by the central controller. To determine the absolute positions of the tagged assets, the mobile tag readers will typically require their absolute positions to be known, since the tag readers may generate information regarding the position of the tags relative to the readers.

Some embodiments of the present invention can result in lower system operation and maintenance costs and increased flexibility for many applications in which a large number of assets are to be tagged and inventoried in an enclosed facility. This is especially true for situations where the assets may remain stationary for extended periods. In these cases, a small number of tag readers can be used to traverse a facility and inventory or track a large number of tagged items distributed throughout the facility, rather than have continuous full coverage of the entire facility at all times by a fixed infrastructure. Hence, the tag readers may be mounted to a means of translation, such as a cart, forklift, human, animal, or other mobile apparatus or vehicle. In this way, the

position of the movable tags may be determined relative to the tag readers by either having the tag readers cooperate and use measurements from more than one tag reader, or by using multiple measurements made by a single moving tag reader, or by using data collected by a tag reader which is downloaded to a central controller capable of such determination.

While the present invention can be directed at RTLS using RFID or other tagging and positioning systems, it is meant to cover real time systems, which determine the tag/tag reader positions continuously, as well as non real time systems, which determine the positions at discrete time intervals, or after the collection of the required data altogether. Accordingly, some embodiments are described, wherein the determination of tag and/or tag reader positions is done after the tag-tag reader communications data has been collected.

Accordingly, one embodiment of the present invention relates to a positioning system, comprising: a tag, adapted for coupling to an asset, having an unknown tag position; and a tag reader, adapted to be coupled to a mobile apparatus while in operation, having a tag reader instantaneous position; wherein the tag reader is adapted to generate information suitable for determination of a distance between the tag position and the tag reader instantaneous position; and wherein the information is a time-of-flight of a signal traveling between the tag and the tag reader.

Another embodiment relates to A positioning system, comprising: a tag, adapted for coupling to an asset, having an unknown tag position; and a tag reader, adapted to be coupled to a mobile apparatus while in operation, having a tag reader position; wherein the tag reader is adapted to generate information suitable for determination of a distance between the tag position and the tag reader position; and wherein said information is a signal strength of a communication between the tag and the tag reader indicating proximity of the tag to the tag reader; and wherein an estimate of the tag position, based on the information from the tag reader, is available on a central controller that is not co-located with the tag reader.

Yet another embodiment provides A positioning system, comprising: a tag, adapted for coupling to an asset, having an unknown tag position; and a tag reader, adapted to be coupled to a mobile apparatus while in operation, having a tag reader instantaneous absolute position; wherein the tag reader is adapted to generate

The invention is described with reference to the following drawings, in which similar reference numbers indicate similar structures.

Fig. 1 is a schematic block diagram of an asset tracking system;

Fig. 2 shows a tag reader communicating with a tag at two different positions;

Fig. 3 shows a tag reader communicating with two different tags at one position;

Fig. 4 is a schematic block diagram of an arrangement of calibration tags used to determine a tag reader position;

Fig. 5 shows an arrangement of synchronized calibration tags;

Fig. 6 shows an arrangement of calibration tags for operation with a tag reader having constrained movement;

Fig. 7 is a schematic block diagram of an exemplary RFID tag; and

Fig. 8 shows an example of a RFID tag datagram protocol.

Detailed Description

Figure 1 is a schematic block diagram of an asset tracking system 1. In this embodiment, a plurality of tags 2 are associated with, e.g., attached to, a corresponding asset (not shown for clarity). The assets may be machinery, equipment, people, products in a warehouse, products being manufactured, vehicles, and/or any other object. The assets and the associated tag 2 may be movable or stationary. If the assets and tags 2 are movable, the assets may move under their own power, such as a car or truck, or may be moved by another device, such as a forklift. Movable assets may remain stationary for extended periods, such as one day, week, month, year, etc., depending on the application.

The tags 2 may be any type of tag, such as short range and long range RFID tags, Modulated BackScatter (MBS) tags, infrared tags, ultrasonic tags, and so on. The tags 2 may be self-powered, e.g., by a battery, solar cell or other power supply, or may be powered by an external source, such as a received electromagnetic signal. The tags 2 may lie dormant for periods between "waking up" and transmitting a signal, or the tags 2 may be awakened upon receiving a signal, such as an electromagnetic signal in a specific frequency range, and prompted to respond to the received signal. Signals sent by the tags 2 may include any suitable information, such as an identification code associated with the tag 2 and the corresponding asset, a time indication, position coordinates for the tag 2, and so on. The tags 2 may be associated with, or incorporate, devices that provide

information to the tag 2, such as a GPS device to determine position coordinates of the tag 2, tamper sensors that indicate whether the tag 2 and/or the asset has been tampered with, temperature sensors, and so on.

The tags 2 communicate with one or more tag readers, which may be mobile tag readers 3, and/or fixed tag readers 11. Tag readers are also called interrogators. Although only one mobile tag reader 3 and one fixed tag reader 11 are shown in Fig. 1, one or more of each may be used in a real system. Communication between the tags 2 and the tag readers can be used to gather information that may be relayed to a central controller 10 over wired or wireless communication channels, for example, by transmitting data to a wireless communications means 6 coupled to the central controller 10.

The central controller 10, or a base station, can have several functions, including:

To receive and consolidate tag information from multiple fixed and mobile readers over time.

To convert relative and absolute position raw data into logical locations. This function may also reside to a certain extent in the readers.

To make position and location data available to end-user applications.

In the PinPoint system, these functions are implemented on a computer running the Windows NT operating system. The functions can be configured to use one or more computers on a network. A "locator service" may then convert the raw tag or distance information into position information.

As an example, the position or location of the tags 2 relative to the mobile tag reader 3 and/or fixed tag reader 11 and/or a fixed geographic reference point may be determined through a communication. Other information may be gathered, such as that provided by the tamper, temperature or other sensors associated with the tag 2.

Communication between the tags 2 and the mobile tag reader 3 and the fixed tag reader 11 is typically wireless, may be one- or two-way communication, and may use any number of RF frequency bands, infrared electromagnetic frequencies, and/or acoustic/ultrasonic communication. Communication between the mobile tag reader 3 and the fixed tag reader 11 and the central controller 10 may be wireless, wired, or a combination of wireless and wired, and may use any suitable electromagnetic, ultrasonic, or other carrier. Wired communication is intended to include communication through

metallic conductors as well as optical fibers or any other physical media or devices that carry the communication signals. Any suitable protocol and/or data format may be used for the communication between the tags 2, the mobile tag reader 3, the fixed tag reader 11 and the central controller 10. For example, the tag reader 3 may store information gathered as it moves among the tags 2 and transfer the information to the central controller 10 by a wired link, e.g., through a plug-in connection to the central controller 10, or by wireless communication to the fixed tag reader 11 which relays the information to the central controller 10 by wire.

The tag reader 3 may be carried by a mobile apparatus, such as a vehicle 4, so that the tag reader 3 can be moved relative to the tags 2. The mobile apparatus may be any type of movable device, such as a car, golf cart, remote-controlled vehicle, aircraft, marine vessel, trailer, train car, shipping container, robot, forklift, conveyor belt, elevator, a track- or wire-guided shuttle, postal package, cargo, luggage, and so on. Thus, the mobile apparatus may be freely movable, i.e., has no defined path or track that must be followed, such as a car driven by a person, or may follow a defined path, such as a shuttle or other device that travels along a track attached to a floor, wall or ceiling of a facility. The tag reader 3 may also be carried by a human or animal, e.g., as the human or animal moves around a storage facility. For example, the tag reader 3 may be associated with a portable device carried by a security guard, incorporated into a cart carrying meals in a hospital, or embedded in a handheld computer, telephone, or Personal Digital Assistant (PDA), used for other purposes.

Since the fixed tag reader 11 is fixed in position, it can receive signals from the tags 2 and/or the central controller 10 can determine the position of the tags 2 relative to the known position of the fixed tag reader 11 or a plurality of fixed tag readers 11. However, the tag reader 3 is mobile, and thus the absolute position of the tags 2 read by the tag reader 3 is determined based on the position of the tags 2 relative to the tag reader 3 and the position of the tag reader 3 relative to some known reference point. The position of the tag reader 3 may be determined by the tag reader or the central controller 10 in a variety of ways. For example, the tag reader 3 may be associated with a differential GPS that determines latitude and longitude coordinates for the tag reader 3, or the asset tracking system 1 may include calibration tags 5 that are fixed in known positions. The calibration tags 5 may be any type of suitable tag, such as those used for

the asset tags 2. By communicating with the calibration tags 5, the tag reader 3 may obtain information suitable for determining the position of the tag reader 3 relative to the calibration tags 5, and thus the tag reader 3's absolute position in the system 1. Determination of the position of the tag reader 3 may be made by the tag reader 3 or by the central controller 10 based on information received from the mobile tag reader 3 or the fixed tag reader 11. For example, the tag reader 3 may be periodically interrogated by the fixed tag reader 11, or otherwise periodically transmit information to the fixed tag reader 11 without interrogation. Based on this communication, the central controller 10 may determine the tag reader 3's absolute position.

The position of a tag 2 relative to the tag reader 3 may be determined in a variety of ways, depending on the type of tag 2 or tag reader 3. For example, the tag reader 3 may send a signal to the tag 2 that is transponded by the tag 2 back to the tag reader 3. The tag reader 3 may determine the position of the tag 2 relative to the tag reader 3 based on information in the signal received from the tag 2. For example, the tag reader 3, central controller 10 or other device may determine the actual distance of the tag 2 from the tag reader 3 based on the travel time-of-flight of the signal(s) between the tag reader 3 and the tag 2. The travel time-of-flight may be a time for a signal to travel one way between the tag reader 3 and the tag 2, or a time for one or more signals to travel both ways between the tag reader 3 and the tag 2. A direction in which the tag 2 is located relative to the tag reader 3 may also be determined, e.g., based on the direction in which a signal sent by the tag 2 is received at the tag reader 3 using a directional antenna or array. The position of a tag 2 may also be actually included in the signal sent by the tag 2 to the tag reader 3, e.g., where the tag 2 is associated with a GPS or other device that determines the tag 2 absolute position and provides the position information to the tag 2 for transmission to the tag reader 3.

The position of a tag 2 may also be determined based on both communication between the tag 2 and the fixed tag reader 11 and communication between the tag 2 and the tag reader 3. That is, the fixed tag reader 11 and central controller 10 may interrogate the tag 2 and determine a distance separating the fixed tag reader 11 and the tag 2. The tag reader 3 may do likewise and determine a distance between the tag reader 3 and the tag 2. Based on a known absolute position of the tag reader 3, the absolute position of the tag 2 can be determined using the two distances.

Using multiple communications between moving tag reader 3 and a stationary tag 2, the relative position of tag 2 with respect to tag reader 3 can be determined. Since the tag reader 3 is in motion, the two distinct communications with tag 2 occur at two tag reader positions, A and B. The two communications yield two distance measurements, A2 and B2, which represent the separation between tag 2 and positions A and B respectively. Assuming that tag 2 was stationary, the position of tag 2 can then be calculated using basic geometry if enough additional data is also known, such as any two of the following:

Position A (e.g., using GPS)

Position B (e.g., using GPS)

Distance between A and B (e.g., using odometry)

Direction of a vector passing through A and B (e.g., compass heading).

The system described above will constrain the tag 2 position to two points symmetrically located about a line connecting A and B. To further determine which of the two possible positions is the true position of tag 2, the mobile reader can use a directional antenna, for example measuring the half plane of stronger signal strength.

Alternately, the mobile reader 3 can travel in a curved path, and use either a directional antenna or an omnidirectional antenna with multiple communication information taken at multiple positions to determine the tag 2 position.

As discussed above, the positions A or B of the tag reader 3 may be determined in a variety of ways, such as by equipping the tag reader 3 with a differential GPS that determines the latitude and longitude for the positions A and B, for example, by fixed tag readers 11 interrogating a mobile tag reader 3, by the tag reader 3 communicating with calibration tags 5, and so on.

Many of the concepts disclosed above can be enhanced by the use of directionally-sensitive communication between the tags and the tag readers. For example, by using directional antennas or antenna arrays, it is possible to improve the positioning accuracy and/or reduce the number of communications or tags required to obtain the desired positions.

The tag reader 3 may be equipped with one or more directional antennas to determine a direction from which a signal from a tag 2 is received. In an embodiment of the PinPoint Corporation Local Positioning System (LPS), each mobile tag reader 3 or

fixed tag reader 11 may support up to 16 antenna modules. Each antenna has a half power beam width (HPBW) of approximately 25 degrees on one axis, and 80 degrees on the other axis. Installing these 16 antennas in a circle, with the beam oriented vertically, results in a "pie" configuration, with each "slice" covering 22.5 degrees with some overlap. Tags 2 high overhead can be read in this configuration. Configuration details depend on the antenna design; the main goal (for the example in Fig. 2) being to use the beam pattern to distinguish between port and starboard.

Tags 2 can be configured to transmit frequently enough to be communicated with at least twice by a tag reader 3 while the tag reader 3 is in range. This approach is necessary when tag readers 3 move through a facility specifically for the purpose of inventory or "taking attendance" of tags 2 and corresponding assets. As one example, a tag reader 3 moving at 15 miles per hour covers about 22 feet per second. PinPoint LPS tags 2 are designed to "wake up" asynchronously about every 3 seconds (the factory default). In some applications, tags 2 wake up less frequently for higher system capacity and/or longer tag battery life. With some percentage of misreads and/or packet collisions, the tag reader 3 may not get at least two reads needed in some cases to determine the tag 2's position. This problem can be mitigated by combining of one or more of the following techniques:

- The tag 2's Automatic Gain Control (AGC), determines that RF or other energy in the tag reader 3's interrogation frequency is in the environment. If no such energy is detected while the tag 2 is transmitting, the tag 2 shuts down, thus saving power when no tag reader 3 is in range. Alternatively the tag 2 does not transmit any energy during this initial "test", thus further improving battery life.
- If tag reader-like RF or other energy is detected, the tag 2 transmits more frequently for a period, say once per second for 10 seconds. The tag reader energy may be coded, such as by using ON-OFF Keying (OOK), or as a beacon that can be distinguished from noise in a communication frequency band.
- When the tag reader 3 has collected enough information from a particular tag 2, it sends an on-off keyed acknowledgement (ACK) to the tag 2, thus informing the tag 2 to revert to normal mode. The tag 2 detects the on-off

signaling by monitoring the AGC. A simple form of acknowledgement is for the tag reader 3 to transmit the interrogation signal for an extra few bit periods of 19 microseconds each, such as 38 microseconds corresponding to 2 bit periods. The tag 2 detects this acknowledgement by noting the power level, and also noting a decrease in the power level at the expected time.

In an alternative design, the tags 2 transmit much less frequently, such as once per minute. A population of tag readers 3 are mounted on devices, such as forklifts 4, that move frequently among the population of tags 2. While a given forklift 4 is in range of a given tag 2, it may or may not read the tag 2. However, over a period of time, each tag 2 is seen by multiple tag readers 3 from multiple positions, and a picture of the tag 2's position is built up by combining such reads.

If it is necessary to determine asset position, i.e., tag 2 position, in 3 dimensions, antennas or antenna modules may be placed at two heights. For example, one interrogator can be positioned near ground level, while another interrogator can be mounted higher up, e.g., on a pole, with more height providing higher accuracy in the vertical direction. A distance difference between the two antennas on the vertical axis can be used to solve for height using basic geometry. A single omnidirectional antenna module can be used for this purpose.

The accuracy of a tag reader 3 to determine the position of a tag 2 is only as good as a real-time estimate of the tag reader 3's position. In addition, since the tag reader 3 may actually be moving relative to the tag 2 during communication, i.e., the tag reader 3 is at position 1 when sending an interrogation signal and at position 2 when receiving a transponded signal from the tag 2, the tag reader 3 position may be difficult to exactly determine. (In most cases, however, the slight movement of the tag reader 3 during communication with a tag 2 may be ignored as it is extremely small compared to the typical distance between the tag reader 3 and the tag 2 and/or the distance measurement errors intrinsic to the system. In this application, such slight movement has been assumed to be negligible, but in some cases it may be necessary to compensate for movement of the tag reader 3 during communication with a tag 2. Some methods such compensation are described below.) Several means are available to determine the tag reader 3's position. For example, the tag reader 3 may be associated with a GPS that provides information regarding the tag reader 3's absolute position. However, GPS

signals may not always be available, such as indoors, where GPS signals are unreliable or unavailable. When GPS is unavailable, the tag reader 3 must use different means to determine its own location. For example, the position of the tag reader 3 may also be determined and/or predicted, e.g., by using the speed and time of travel of the tag reader 3 in a known direction, by using inertial navigation systems, gyroscopes, compasses, odometers, speedometers, timers or other devices.

Fig. 3 shows another way that a tag reader 3 may determine, or obtain information sufficient to determine, the position of the tag reader 3. In the example of Fig. 3, the tag reader 3 communicates with two or more calibration tags 5. The calibration tags 5 may send information to the tag reader 3 indicating the precise position of the calibration tag 5, or the tag reader 3 or central controller 5 may store position information for each of the calibration tags 5 in the system 1 and correlate the tag 5's position with an identification number for the calibration tag 5 in a memory. The tag reader 3 may determine the distance and/or the direction at which the tag 5 lies relative to the tag reader 5 and thereby determine the position of the tag reader 3 relative to the calibration tags 5. Communication with a single calibration tag 5 may be enough to determine the precise position of the tag reader 3, or communication with multiple calibration tags 5 may be necessary, e.g., where the tag reader 3 position is determined using triangulation, signal strength, or distance measurement only techniques.

The calibration tags 5 may be embedded in the floor, walls, posts, ceiling or other structures in a facility. As one example, passive RFID tags (not requiring batteries) are buried in the floor at fixed locations, such as at the end of aisles in a warehouse. Relatively low frequency RFID tags, such as 125 KHz or 13.56 MHz, are well-suited to this purpose, do not interfere with a higher-frequency RTLS tags, and are available from a variety of vendors. Pairs of tags 5 spaced a meter or two apart may indicate, or provide information suitable to determine, direction of movement of the tag reader 3. An RFID reader in the tag reader 3 calibrates its position whenever it drives by one of these tags 5. In a warehouse, for example, tags 5 can be placed at the end of each aisle of racks. In addition to such calibration steps, various off-the-shelf technologies, such as speedometers, compasses, gyroscopes, and inertial motion sensors, may be used by the tag reader 3 or central controller 10 to estimate the position of the tag reader 3.

An alternative implementation of this concept uses RTLS tags as calibration tags 5 positioned in pre-surveyed locations. An example using 3D-iD tags and associated technology is described in connection with Fig. 4. A tag reader 3 moves along the path P1, P3, P2, P4. The tag reader 3 uses odometry and/or inertial technology, such as a speedometer combined with a compass and/or gyroscope, to measure the distance traveled and changes in direction. A calibration tag 5T1, which is in a known position, transmits when the tag reader 3 is in locations P1 and P2, resulting in distances R1 and R2 determined by the tag reader 3 or other device. If the distance between P1 and P2 is measured directly by the motion of the tag reader 3, the shape of the triangle P1-P2-5T1 can be determined. Another calibration tag 5T2 is also in the environment, and transmits when the tag reader 3 is in locations P3 and P4, resulting distances R3 and R4. Distance R3 can be used to determine the orientation of triangle P1-P2-5T1, and hence the starting point and direction of path P1-P2. Similarly, distance R2 can be used to determine the starting point and direction of triangle P3-P4-5T2. Working in this fashion, it is possible to combine readings from multiple tags 5 to track and continuously recalibrate the position of the tag reader 3. For higher accuracy, extra calibration tags 5 may be placed in the environment, allowing errors to be averaged out.

In addition, by placing some constraints on the system, it is possible to accurately determine the position of the tag reader 3 based purely on the signals of the calibration tags 5, e.g., without using inertial technology. The calibration tags 5 may be configured to transmit relatively frequently. Referring to Fig. 4, assume that calibration tags 5T1 and 5T2 are configured to transmit once per second. If the direction and speed of the tag reader 3 are assumed to be constant over a one-second period, points P1, P3, and P2, may be assumed to fall along one line, and points P3, P2, and P4 along another line.

Another approach is to configure groups of calibration tags 5 to transmit at about the same time. For example, a group of several calibration tags placed in the ceiling of a warehouse may be wired together, and be configured to transmit in rapid succession every several seconds, as illustrated in Fig. 5. Since each tag 5's datagram is about 2.5 milliseconds long, a group of ten such tags 5 can complete their transmissions in 25 milliseconds. Fig. 5 shows transmission from five tags 5 being received by the tag reader 3. Unless the tag reader 3 is moving very quickly, it will be substantially stationary during that period, as indicated by the slight motion of the tag reader 3 in the

illustration. (Note that using 3D-iD technology allows distances to be measured with an accuracy of about ±2 feet. A forklift traveling at 30 mph travels about one foot in 25 milliseconds, thus adding little to the system uncertainty.) Since the calibration tags 5 transmit every 3 seconds, a location is fixed every 3 seconds. The tag reader 3's path is estimated by interpolating between known positions.

Another approach is to assume a constrained path for the tag reader 3. For example, in a warehouse with racks, forklifts having tag readers 3 attached can be assumed to travel between racks, not through them, as shown in Fig. 6. A tag reader 3 located between Rack 2 and Rack 3 can communicate with tags 5T1, 5T2, 5T4, and 5T5. The dotted lines indicate that the communications through a rack are likely to be along an indirect path, making them somewhat longer than their actual distance. However, the communication along paths R4 and R5 will be on a direct path, and in any case are short as compared to communications from tags 5T1 and 5T2 along paths R1 and R2. Thus, the short reads from calibration tags 5T4 and 5T5 show that the tag reader 3 is located in an aisle between Rack 2 and Rack 3; and the distance measurements to calibration tags 5T4 and 5T5 indicate the tag reader 3's position in the row.

Data from the tag reader 3 can be reported to the central controller 10 by wireless means, providing an immediate data link. Alternatively, the data can be collected into the memory of the tag reader 3, and downloaded in a batch when the it returns to a base station. As noted previously, the batch link may be wireless. The central controller 10 may keep track of aisles that have been covered. If certain aisles have not been covered recently, the system software highlights this.

The use of mobile tag readers 3 may be combined with a fixed infrastructure, as discussed above. For example, on a loading dock, where trucks are continuously coming and going, a fixed RTLS infrastructure is best deployed. But if there is a large facility also where trailers are parked and/or stored, a mobile tag reader 3 can be used to take inventory periodically. The choice between the two technologies is a cost/benefit decision. On the cost side, one must consider the tradeoff between the labor needed to drive the tag reader 3 through the facility, vs. the cost of a fixed infrastructure (assuming that the tag reader 3 is moved by a human-driven vehicle - otherwise the cost of an automated mobile apparatus, such as a robot or track-guided shuttle may be considered). On the benefit side, a basic consideration is the value of current information that a fixed

infrastructure can provide. A single tag reader 3 provides an entry-level system, with additional tag readers 3 and fixed infrastructure, such as antennas 11 and so on, available as upgrades.

The present invention may determine tag-tag reader distance using methods other than signal time-of-flight. Some systems may employ signal strength as a proximity indicator. Ultra High Frequency (UHF) communications are one example of systems which can use signal strength as a measure of distance, since the electromagnetic radiation field generally weakens as a function of distance from the source of the radiation.

Several embodiments described above have focused on reading and locating 3D-iD tags from a mobile tag reader 3, and details regarding 3D-iD tags 2 and 5 are provided below. These detailed examples are not meant to be inclusive of the broad range of possible applications of the present invention, some of which were briefly mentioned above. It should be clear that other types of tags, including non-RF types and non-electromagnetic types, may also be used. The same principles may be applied to other systems, although possibly with lower performance. For example, UHF beaconing tags may be read from a mobile reader 3. Signal strength is used to very roughly determine distance from such tags to the readers. Differential GPS and/or calibration tags 5 in the environment may be used to roughly determine reader location. While the implementation is simpler and the accuracy is lower, the principles are the same.

As shown in Fig. 7, a 3D-iD asset tracking system 1 may include one or more multi-antenna module 113 cell controllers 112 that send Direct Sequence Spread Spectrum (DSSS) interrogation signals to tags 102 within range of an antenna module **113**. The tags 102 transpond this interrogation signal at low power. Information from the cell controllers 112 is sent to a central controller 110 using a TCP/IP protocol, typically via an Ethernet connection. The system 1 may also include a mobile tag reader 103 having a configuration of any of those described above, and may communicate with tags 102 in a manner similar to that described below with respect to the cell controllers 112. The mobile tag reader 103 may also communicate with the a cell controller 112 or the central controller 110. It should be understood that the antenna modules 113 may be eliminated and only mobile tag readers 3 used, if suitable.

The cell controllers 112, central controller 110 and/or the tag reader 3 can be a programmed general purpose computer, or network of programmed general purpose computers, along with other circuitry and devices required to perform the desired input/output or other functions. The controllers 110/112 or the tag reader 3 can also include other devices, such as a monitor, printer or other display device, a keyboard, user pointing device, touch screen or other user interface, storage devices, communication devices, or other electronic circuitry or components. The controllers 110/112 or the tag reader 3 can also be or include other programmed or hard-wired electronic devices, such as application-specific integrated circuits (e.g., ASICs), discrete element circuits, FPGAs, etc.

More specifically, cell controllers 112 emit a direct sequence spread spectrum interrogation signal in the 2400-2483.5 MHz ("2.45 GHz") band to tags 102. Tags 102 in range up-convert the interrogation signal's center frequency from 2442 MHz to 5800 MHz, and ensure that emissions are limited to the 5725-5875 MHz ("5.80 GHz") band. Tag 102 ID information is modulated onto the return signal, which is transmitted back to the cell controller 112 and received at low power via an antenna module 113. The cell controller 112 extracts the tag 102 ID from this return signal, and also determines the tag 102's distance from the antenna module 113 by measuring the round trip time of flight of the communication between the antenna module 113 (tag reader 3) and the tag 102. Both the interrogator and the tag 102 signal comply with current FCC Part 15 regulations, so no license is needed for operation.

In the implementation shown in Fig. 7, the cell controller 112 is attached to 4 antenna modules 113a-113d. Multiple antenna modules 113 may be used to read tag 102 distance from multiple directions, providing information to determine tag 102 position. Alternative implementations of just one antenna module 113, or 16 or more antenna modules 113, are possible.

The cell controller 112 cycles among its antenna modules 113a-113d, determining the distance between the antenna modules 113 and a given tag 102, if possible. Once the distance to three antenna modules 113 is found, the tag 102's position in space can be estimated. In many situations, it is possible to get a good estimate of tag 102 position from fewer than three antenna modules 113 and/or tag reader 3 positions.

For example, a grocery store aisle can be covered by two antenna modules 113, one at each end, and most hallways can be similarly covered.

As the tag 102 will transpond any energy received in the 2400-2483.5 MHz ISM band, a wide variety of interrogation signals might be used to read the tag 102. The commercial implementation of 3D-iD is intended to read tags 102 at maximum range and with highest position accuracy, using 127 chip sequences at a rate of 40 megachips per second. 40 megachips per second is the maximum rate supported by the 2400-2483 MHz band.

Tags 102 typically operate according to a "tag-talks-first" paradigm. Tags 102 may wake up spontaneously, transmit their unique codes, and then go back to sleep. Each transmission is short, on the order of 2.5 milliseconds. The sleep time can vary based on application requirements. For example, tags 102 attached to personnel might transmit every two seconds, while tags 102 attached to inventory might be set to transmit once per minute.

The tag data protocol includes a capability to pass along information provided by a closely integrated device. For example, a specialized tag 102 integrated with a temperature sensor can be used to report current and historical environmental data. As another example, personnel tags 102 include a "call button". To support such low-bandwidth communication, the data protocol may include bandwidth to uplink a small amount of status information.

The tag 102 receives a DSSS signal from the interrogator, centered at 2442 MHz or another frequency in the 2400-2483 MHz band, at a receive antenna 1021. This signal is first filtered by a filter 1022 and amplified by an amplifier 1023. The signal is then modulated by a modulator 1024 that either passes the signal unchanged, or inverts the phase by 180°. The modulator 1024 operates under microprocessor 1025 control. The modulated signal is then filtered by a filter 1026, amplified by an amplifier 1027, and then mixed at a mixer 1028 with the output of a 3358 MHz oscillator 1029, resulting in a signal of 2442+3358=5800 GHz. This 5800 GHz response is then filtered by a filter 1030, amplified by an amplifier 1031, filtered again by a filter 1032, and transmitted though an antenna structure 1033. An Automatic Gain Control (AGC) 1034 keeps the operation of tag components in an optimal range. Tag operation is controlled by the microprocessor 1025, such as a PIC processor from Microchip.

Note that the DSSS signal is not demodulated by the tag 102; it is simply passed through. This provides the system with the performance of a DSSS system without the necessity of a DSSS modulator or demodulator on the tag 102. In enhanced implementations of this design, an Rx Threshold Detector may be added to the receiver, providing support for an on-off keyed (OOK) forward link.

Fig. 7 is intended to clarify the transponding and modulation operations that might occur in the RFID tag 102. No implementation recommendation or constraint is intended with regard to nature and placement of components, and the modulation result may be made consistent with the description above and the specifications in Appendix A.

The RFID tag 102 normally performs two basic functions.

- It provides a RF mirror (frequency translation) so the interrogator can locate it.
- It modulates the interrogator signal to transmit the tag information back to the interrogator using a tag protocol.

The tag 102 spends most of its time in the sleep state. During its active interval the tag 102 "wakes up" by stabilizing its internal oscillators, calculating a Cyclic Redundancy Check (CRC), initiating radio transmission and modulation, sending its datagram and finally returning to the sleep state.

Fig. 8 shows an example of a tag datagram used by the tag 102 shown in Fig. 7 having nine contiguous sections. The sections are the tag preamble 81, the end preamble 82 (optional), the start data sequence 83, the datagram version identifier 84, the tag serial number 85, the status bits 86, the tag data 87, the CRC 88, and end bit 89. This datagram may be sent once during the tag 102 RF-on cycle. Each individual bit may span a 19.05 microsecond period, corresponding to an interrogator signal of six 127-chip sequences at a rate of 40 megachips per second.

The tag preamble 81 may used by the interrogator (cell controller 112 or tag reader 3) to perform three functions:

1. To search for the tag 102 sequentially through each of the interrogator's antennas. If a tag 102 is seen in this search process, the interrogator then proceeds with the subsequent steps;
2. To determine the distance to the tag 102 from each antenna that sees the tag;

3. To pick the best antenna for collecting the rest of the datagram.

The tag preamble 81 includes a constant bit pattern of 38 effective one bits. A one bit is defined as having no phase change, so the preamble 81 has a constant phase. The preamble 81 includes 31 bits for determination of distances from each of up to 16 antennas, and 7 bits to allow for cell controller 112/tag reader 3 overhead. If fewer than 16 antennas are connected and/or supported, the cell controller 112/tag reader 3 can reduce its duty cycle accordingly with minimal impact on performance.

End preamble 82 allows the cell controller 112/tag reader 3 to synchronize its baseband clock. The end preamble 82 begins by the tag 102 shutting down its transmitter for 6 microseconds. The rest of the first bit interval, and the remaining 3 bits allows the interrogator to reacquire the tag signal. This field is optional, and improves reliability in certain interrogator designs.

The start data sequence flag 83 includes a "010" bit pattern to indicate end-of-preamble. The tag version field 84 follows the start data sequence 83 and includes 4 bits that may be used to support future enhancements to the protocol and to provide a signal for future interrogators to enable backward compatibility. In this version of the protocol, its value is "0000".

The tag serial number 85 follows the tag version 84 and includes 32 bits organized as four bytes (msb). There is no special meaning to the 4 bytes other than the tag serial number 85.

The tag status or housekeeping field 86 follows the tag identification 85 and includes 8 bits that may be used for fixed housekeeping purposes. The 8 bits are UUUUUUTB (msb), where B=1 indicates low battery and T=1 is a tamper indicator. For personnel tags 102, the tamper detect bit may be used to indicate use of a call button. The six remaining bits are left unspecified, and are intended for application-specific uses.

The tag data field 87 follows the status field 86, and includes 24 bits whose function varies by application. A typical application is to report the status of an environmental sensor, or to report status information from tagged equipment.

The next to last field is a CRC 88. The CCITT 16-bit CRC 88 takes as input: the version, serial number, status and data fields.

The final field is used as a stop bit 89, which may be a replication of the last bit in the checksum field and allows for a smooth and controlled end of acquisition within the interrogator and graceful tag shutdown. It is also possible for enhanced tags 102 to receive on-off keyed (OOK) messages from the interrogator immediately following the end of the datagram, for purposes such as acknowledgements, changes in tag parameters (such as sleep times), or commands to devices attached to the tags 102.

Each bit of the tag datagram may last for 19.05 microseconds and there are effectively 126 bits in a datagram (excluding the optional end premable 82), so the datagram may last for about 2.4 milliseconds.

At the end of a tag transmission, the tag 102 may go to sleep for an amount of time pre-programmed into its microprocessor 1025. A typical three second sleep time provides about a 1000:1 duty cycle. It is desirable to include a randomized component in the sleep cycle to prevent pairs of tags 102 from transmitting in a repeated synchronized fashion. The randomization function may vary according to the implementation of the sleep cycle. A randomization formula that varies as a function of tag ID is recommended. This is an average, accounting for randomization.

While the invention has been described in conjunction with specific embodiments thereof, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art. Accordingly, embodiments of the invention as set forth herein are intended to be illustrative, not limiting. Various changes may be made without departing from the invention.

Appendix A

Forward Link Parameters

Parameter Number	Parameter Name	Description
F 1	Operating Frequency Range	2400-2483.5 MHz
F 1a	Default Operating Frequency	2442 MHz (center frequency)
F 1b	Operating Channels	2442 MHz only (Center Frequency)
F 1c	Operating Frequency Accuracy	± 25 ppm maximum.
F 1d	Frequency Hop Rate	Not applicable
F 1e	Frequency Hop Sequence	Not applicable
F 2	Occupied Channel Bandwidth	The 20 dB bandwidth is regulated by FCC Part 15, Section 15.247
F 3	Interrogator Transmit Maximum EIRP	The maximum EIRP transmitted by the interrogator antenna is regulated by reference document FCC Part 15, Section 15.247. This maximum is 30 dBm output from the interrogator and 36 dBm EIRP from the interrogator transmit antenna.
F 4a	Interrogator Transmit Spurious Emissions, In-Band	Not applicable.
F 4b	Interrogator Transmit Spurious Emissions, Out-of-Band	The interrogator shall transmit in conformance with spurious emissions requirements defined in reference FCC Part 15, Sections 15.205 and 15.209.
F 5	Interrogator Transmitter Spectrum Mask	The interrogator transmitter spectrum mask is regulated by reference document FCC Part 15, Section 15.247. The peak power spectral density conducted from the intentional radiator to the antenna shall not be greater than 8 dBm in any 3 kHz band during any time interval of continuous transmission.
F 5a	Transmit to Receive Turn Around Time	Not applicable.
F 5b	Receive to Transmit Turn Around Time	Not applicable.
F 5c	Interrogator Transmit Power On Ramp	Not applicable.
F 5d	Interrogator Transmit Power Down Ramp	Not applicable.
F 6	Modulation	DSSS MPSK (BPSK or higher)

Parameter Number	Parameter Name	Description
R 1e	Frequency Hop Sequence	Not applicable.
R 2	Occupied Channel Bandwidth	Up-converted and low-power approximate replica of 2400-2484 spectrum. Matches Interrogator spectral profile in normal operation.
R 3	Transmit Maximum EIRP	The maximum EIRP transmitted by the tag antenna is regulated by reference document FCC Part 15, Section 15.249. This maximum is 50 millivolts/meter measured at a distance of 3 meters. Field strength limits are based on average limits. However, the peak field strength of any emission shall not exceed the maximum permitted average limits by more than 20 dB under any condition of modulation.
R 4a	Transmit Spurious Emissions, In-Band	Not applicable.
R 4b	Transmit Spurious Emissions, Out-of-Band	The tag shall transmit in conformance with spurious emissions requirements defined in reference document FCC Part 15, Section 15.249. Emissions radiated outside of the 5725-5875 MHz frequency band, except for harmonics, shall be attenuated by at least 50 dB below the level of the fundamental or to the general radiated emission limits in §15.209, whichever is the lesser attenuation. Harmonics are limited to 500 microvolts/meter.
R5	Transmit Spectrum Mask	Transponder; not applicable.
R 5a	Transmit to Receive Turn Around Time	Not applicable.
R 5b	Receive to Transmit Turn Around Time	Not applicable.
R 5c	Transmit Power On Ramp	Radio shall be disabled until power on ramp completed.
R 5d	Transmit Power Down Ramp	Radio shall be disabled prior to power down ramp.
R 6	Modulation	DBPSK.
R 6a	Sub-carrier Frequency	3358 MHz (as defined in standard)
R 6b	Sub-carrier Frequency Accuracy	Not applicable
R 6c	Sub-Carrier Modulation	Not applicable
R 7	Data Coding	Phase change of 0 represents 1; phase change of represents 0.

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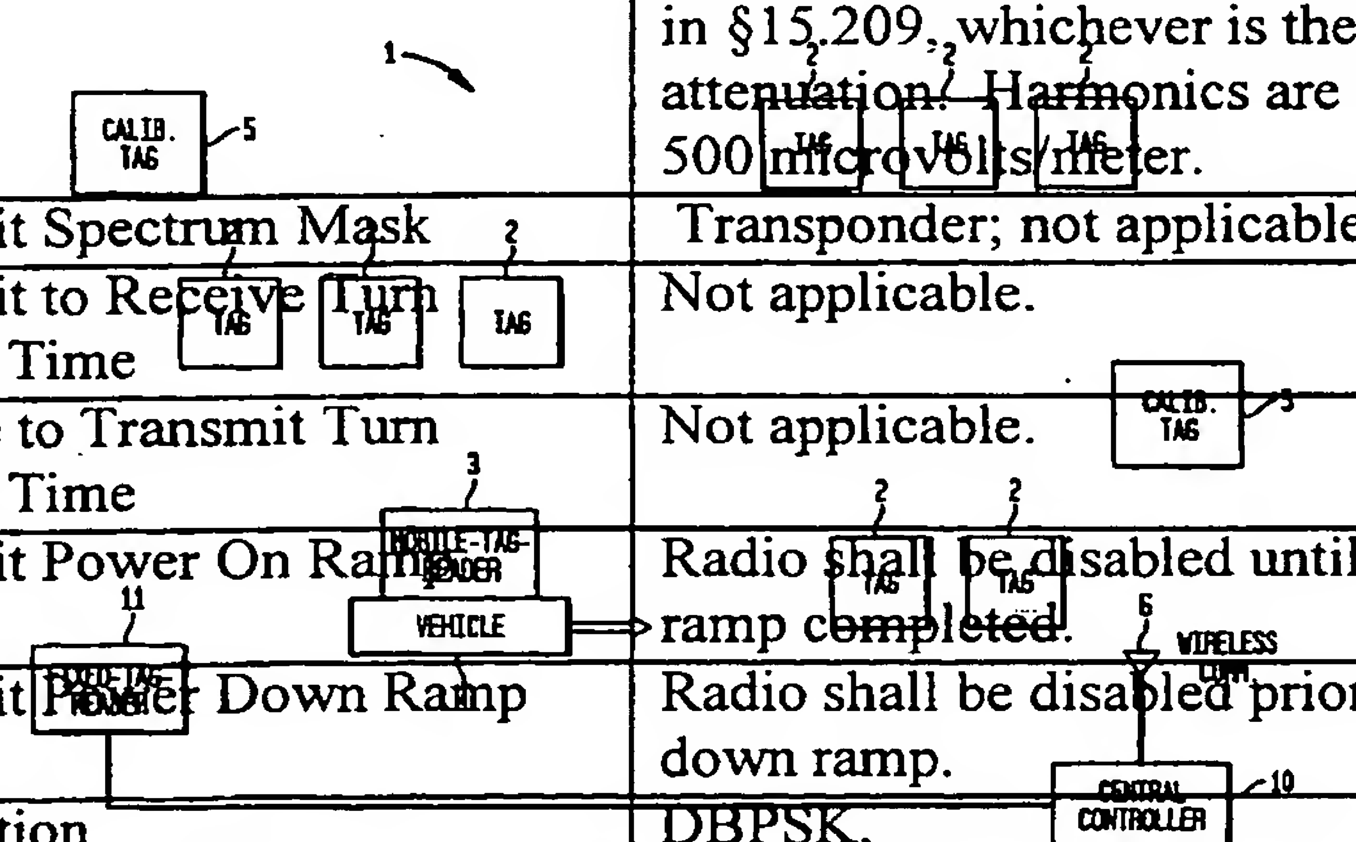

(57) Abstract: A mobile tag reader (3) and method for tracking tags (2) for an inventory control and/or security of distributed assets. Radio frequency identification (RFID) tags (2) may be attached to stationary or moveable assets and communicate with one RFID tag readers (3, 11). Communication may provide information to a central or remote controller (10) about the identity, position and/or the status of the tags (2) and assets. The absolute position of the tagged assets may be determined by the mobile tag reader (3) or central controller (10), and the absolute position of the mobile reader may be ascertained from communications with tags in fixed known locations. Typical applications are for indoor inventory control with the mobile tag readers being mounted to roving trucks, forklifts, or being carried by personnel.

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RFID tags in daily use are short range tags for use in automated gas pump payment and automated highway toll collection. Another example is very small, low-power tags embedded under the skin of household pets, used with a national database for identification of lost animals.

A RTLS may or may not use RFID. For example, while a RTLS employing RFID tags and tag readers is, of course, a RFID RTLS, other RTLS's, such as GPS, infrared, and ultrasonic systems are not RFID systems.

An example of a commercially available RTLS used for tracking and identification of assets is the 3D-iD™ Local Positioning System (LPS) from PinPoint Corporation. 3D-iD is a trademark of the PinPoint Corporation. The Firefly™ system from WhereNet Corporation is another example. Firefly is a trademark of WhereNet Corporation. In contrast to a 3D-iD tag, a Firefly tag is not a transponder; rather it emits a beaconing signal that is simultaneously received by a network of readers, and the readers use differential time of arrival of the beaconing signal to estimate tag position. Other systems include the Electronic Home Arrest Monitoring (EHAM) system from B.I., as well as systems from Savi Technology, Inc. These systems may also use UHF beacons, and estimate tag location based on proximity and/or signal strength. Various other RTLS designs have been proposed and/or commercialized, utilizing GPS, E-911, Doppler shift, infrared emitters, ultrasonic emitters, etc.

As an example, one RTLS using infrared and ultrasonic communication channels has been described, and may be used to determine asset location. The system equips moving assets, such as employees, with a transceiver that periodically emits an infrared flash. Fixed calibration emitters receiving the flash emit an ultrasonic signal in a specific sequence that is received by the transceiver. Based on the time between when the infrared flash was output and the time the ultrasonic signal is received from an emitter, the transceiver or other device can determine the position of the asset relative to the fixed emitters.

In some cases, RFID tags cannot be communicated with by fixed antenna transceivers, preventing an asset locating system from determining where some assets are. For example, some RFID tags can suffer from short operating ranges, and are prone to having their communication signals disrupted by attenuating objects in the communication path. Reflections from reflecting objects in the neighborhood of some

RFID tags can also affect their reliability. Thus, a need exists for a more economical, reliable, and flexible system for coverage of extended facilities, and particularly enclosed facilities where the use of Global Positioning System (GPS) is not possible because communication signals from satellites will not penetrate the structures enclosing the facility. In other applications, the use of GPS is not feasible due to the high cost of placing GPS receivers onto all assets to be tracked. Additionally, such systems often consume too much power to be routinely installed on a large number of items that may ideally be tracked for extended periods of time.

Summary of the Invention

An embodiment of the invention provides a mobile tag reader that can be used to communicate with tags that are either fixed in position or attached to assets that are movable. By communicating with the tags, the mobile tag reader can generate information suitable for determining the absolute position of the tag reader and/or the movable tags. The tag reader may store information about the relative position of assets in its vicinity onboard or transmit this information to a central base station computer, or central controller. The relative and/or absolute positions of the tag reader and the tagged assets may be determined using a positioning system onboard the tag reader, such as a GPS or an inertial navigation system, or the positions may be determined subsequently by the central controller. To determine the absolute positions of the tagged assets, the mobile tag readers will typically require their absolute positions to be known, since the tag readers may generate information regarding the position of the tags relative to the readers.

Some embodiments of the present invention can result in lower system operation and maintenance costs and increased flexibility for many applications in which a large number of assets are to be tagged and inventoried in an enclosed facility. This is especially true for situations where the assets may remain stationary for extended periods. In these cases, a small number of tag readers can be used to traverse a facility and inventory or track a large number of tagged items distributed throughout the facility, rather than have continuous full coverage of the entire facility at all times by a fixed infrastructure. Hence, the tag readers may be mounted to a means of translation, such as a cart, forklift, human, animal, or other mobile apparatus or vehicle. In this way, the

position of the movable tags may be determined relative to the tag readers by either having the tag readers cooperate and use measurements from more than one tag reader, or by using multiple measurements made by a single moving tag reader, or by using data collected by a tag reader which is downloaded to a central controller capable of such determination.

While the present invention can be directed at RTLS using RFID or other tagging and positioning systems, it is meant to cover real time systems, which determine the tag/tag reader positions continuously, as well as non real time systems, which determine the positions at discrete time intervals, or after the collection of the required data altogether. Accordingly, some embodiments are described, wherein the determination of tag and/or tag reader positions is done after the tag-tag reader communications data has been collected.

Accordingly, one embodiment of the present invention relates to a positioning system, comprising: a tag, adapted for coupling to an asset, having an unknown tag position; and a tag reader, adapted to be coupled to a mobile apparatus while in operation, having a tag reader instantaneous position; wherein the tag reader is adapted to generate information suitable for determination of a distance between the tag position and the tag reader instantaneous position; and wherein the information is a time-of-flight of a signal traveling between the tag and the tag reader.

Another embodiment relates to A positioning system, comprising: a tag, adapted for coupling to an asset, having an unknown tag position; and a tag reader, adapted to be coupled to a mobile apparatus while in operation, having a tag reader position; wherein the tag reader is adapted to generate information suitable for determination of a distance between the tag position and the tag reader position; and wherein said information is a signal strength of a communication between the tag and the tag reader indicating proximity of the tag to the tag reader; and wherein an estimate of the tag position, based on the information from the tag reader, is available on a central controller that is not co-located with the tag reader.

Yet another embodiment provides A positioning system, comprising: a tag, adapted for coupling to an asset, having an unknown tag position; and a tag reader, adapted to be coupled to a mobile apparatus while in operation, having a tag reader instantaneous absolute position; wherein the tag reader is adapted to generate

The invention is described with reference to the following drawings, in which similar reference numbers indicate similar structures.

Fig. 1 is a schematic block diagram of an asset tracking system;

Fig. 2 shows a tag reader communicating with a tag at two different positions;

Fig. 3 shows a tag reader communicating with two different tags at one position;

Fig. 4 is a schematic block diagram of an arrangement of calibration tags used to determine a tag reader position;

Fig. 5 shows an arrangement of synchronized calibration tags;

Fig. 6 shows an arrangement of calibration tags for operation with a tag reader having constrained movement;

Fig. 7 is a schematic block diagram of an exemplary RFID tag; and

Fig. 8 shows an example of a RFID tag datagram protocol.

Detailed Description

Figure 1 is a schematic block diagram of an asset tracking system 1. In this embodiment, a plurality of tags 2 are associated with, e.g., attached to, a corresponding asset (not shown for clarity). The assets may be machinery, equipment, people, products in a warehouse, products being manufactured, vehicles, and/or any other object. The assets and the associated tag 2 may be movable or stationary. If the assets and tags 2 are movable, the assets may move under their own power, such as a car or truck, or may be moved by another device, such as a forklift. Movable assets may remain stationary for extended periods, such as one day, week, month, year, etc., depending on the application.

The tags 2 may be any type of tag, such as short range and long range RFID tags, Modulated BackScatter (MBS) tags, infrared tags, ultrasonic tags, and so on. The tags 2 may be self-powered, e.g., by a battery, solar cell or other power supply, or may be powered by an external source, such as a received electromagnetic signal. The tags 2 may lie dormant for periods between "waking up" and transmitting a signal, or the tags 2 may be awakened upon receiving a signal, such as an electromagnetic signal in a specific frequency range, and prompted to respond to the received signal. Signals sent by the tags 2 may include any suitable information, such as an identification code associated with the tag 2 and the corresponding asset, a time indication, position coordinates for the tag 2, and so on. The tags 2 may be associated with, or incorporate, devices that provide

information to the tag 2, such as a GPS device to determine position coordinates of the tag 2, tamper sensors that indicate whether the tag 2 and/or the asset has been tampered with, temperature sensors, and so on.

The tags 2 communicate with one or more tag readers, which may be mobile tag readers 3, and/or fixed tag readers 11. Tag readers are also called interrogators. Although only one mobile tag reader 3 and one fixed tag reader 11 are shown in Fig. 1, one or more of each may be used in a real system. Communication between the tags 2 and the tag readers can be used to gather information that may be relayed to a central controller 10 over wired or wireless communication channels, for example, by transmitting data to a wireless communications means 6 coupled to the central controller 10.

The central controller 10, or a base station, can have several functions, including:

To receive and consolidate tag information from multiple fixed and mobile readers over time.

To convert relative and absolute position raw data into logical locations. This function may also reside to a certain extent in the readers.

To make position and location data available to end-user applications.

In the PinPoint system, these functions are implemented on a computer running the Windows NT operating system. The functions can be configured to use one or more computers on a network. A "locator service" may then convert the raw tag or distance information into position information.

As an example, the position or location of the tags 2 relative to the mobile tag reader 3 and/or fixed tag reader 11 and/or a fixed geographic reference point may be determined through a communication. Other information may be gathered, such as that provided by the tamper, temperature or other sensors associated with the tag 2.

Communication between the tags 2 and the mobile tag reader 3 and the fixed tag reader 11 is typically wireless, may be one- or two-way communication, and may use any number of RF frequency bands, infrared electromagnetic frequencies, and/or acoustic/ultrasonic communication. Communication between the mobile tag reader 3 and the fixed tag reader 11 and the central controller 10 may be wireless, wired, or a combination of wireless and wired, and may use any suitable electromagnetic, ultrasonic, or other carrier. Wired communication is intended to include communication through

metallic conductors as well as optical fibers or any other physical media or devices that carry the communication signals. Any suitable protocol and/or data format may be used for the communication between the tags 2, the mobile tag reader 3, the fixed tag reader 11 and the central controller 10. For example, the tag reader 3 may store information gathered as it moves among the tags 2 and transfer the information to the central controller 10 by a wired link, e.g., through a plug-in connection to the central controller 10, or by wireless communication to the fixed tag reader 11 which relays the information to the central controller 10 by wire.

The tag reader 3 may be carried by a mobile apparatus, such as a vehicle 4, so that the tag reader 3 can be moved relative to the tags 2. The mobile apparatus may be any type of movable device, such as a car, golf cart, remote-controlled vehicle, aircraft, marine vessel, trailer, train car, shipping container, robot, forklift, conveyor belt, elevator, a track- or wire-guided shuttle, postal package, cargo, luggage, and so on. Thus, the mobile apparatus may be freely movable, i.e., has no defined path or track that must be followed, such as a car driven by a person, or may follow a defined path, such as a shuttle or other device that travels along a track attached to a floor, wall or ceiling of a facility. The tag reader 3 may also be carried by a human or animal, e.g., as the human or animal moves around a storage facility. For example, the tag reader 3 may be associated with a portable device carried by a security guard, incorporated into a cart carrying meals in a hospital, or embedded in a handheld computer, telephone, or Personal Digital Assistant (PDA), used for other purposes.

Since the fixed tag reader 11 is fixed in position, it can receive signals from the tags 2 and/or the central controller 10 can determine the position of the tags 2 relative to the known position of the fixed tag reader 11 or a plurality of fixed tag readers 11. However, the tag reader 3 is mobile, and thus the absolute position of the tags 2 read by the tag reader 3 is determined based on the position of the tags 2 relative to the tag reader 3 and the position of the tag reader 3 relative to some known reference point. The position of the tag reader 3 may be determined by the tag reader or the central controller 10 in a variety of ways. For example, the tag reader 3 may be associated with a differential GPS that determines latitude and longitude coordinates for the tag reader 3, or the asset tracking system 1 may include calibration tags 5 that are fixed in known positions. The calibration tags 5 may be any type of suitable tag, such as those used for

the asset tags 2. By communicating with the calibration tags 5, the tag reader 3 may obtain information suitable for determining the position of the tag reader 3 relative to the calibration tags 5, and thus the tag reader 3's absolute position in the system 1. Determination of the position of the tag reader 3 may be made by the tag reader 3 or by the central controller 10 based on information received from the mobile tag reader 3 or the fixed tag reader 11. For example, the tag reader 3 may be periodically interrogated by the fixed tag reader 11, or otherwise periodically transmit information to the fixed tag reader 11 without interrogation. Based on this communication, the central controller 10 may determine the tag reader 3's absolute position.

The position of a tag 2 relative to the tag reader 3 may be determined in a variety of ways, depending on the type of tag 2 or tag reader 3. For example, the tag reader 3 may send a signal to the tag 2 that is transponded by the tag 2 back to the tag reader 3. The tag reader 3 may determine the position of the tag 2 relative to the tag reader 3 based on information in the signal received from the tag 2. For example, the tag reader 3, central controller 10 or other device may determine the actual distance of the tag 2 from the tag reader 3 based on the travel time-of-flight of the signal(s) between the tag reader 3 and the tag 2. The travel time-of-flight may be a time for a signal to travel one way between the tag reader 3 and the tag 2, or a time for one or more signals to travel both ways between the tag reader 3 and the tag 2. A direction in which the tag 2 is located relative to the tag reader 3 may also be determined, e.g., based on the direction in which a signal sent by the tag 2 is received at the tag reader 3 using a directional antenna or array. The position of a tag 2 may also be actually included in the signal sent by the tag 2 to the tag reader 3, e.g., where the tag 2 is associated with a GPS or other device that determines the tag 2 absolute position and provides the position information to the tag 2 for transmission to the tag reader 3.

The position of a tag 2 may also be determined based on both communication between the tag 2 and the fixed tag reader 11 and communication between the tag 2 and the tag reader 3. That is, the fixed tag reader 11 and central controller 10 may interrogate the tag 2 and determine a distance separating the fixed tag reader 11 and the tag 2. The tag reader 3 may do likewise and determine a distance between the tag reader 3 and the tag 2. Based on a known absolute position of the tag reader 3, the absolute position of the tag 2 can be determined using the two distances.

Using multiple communications between moving tag reader 3 and a stationary tag 2, the relative position of tag 2 with respect to tag reader 3 can be determined. Since the tag reader 3 is in motion, the two distinct communications with tag 2 occur at two tag reader positions, A and B. The two communications yield two distance measurements, A2 and B2, which represent the separation between tag 2 and positions A and B respectively. Assuming that tag 2 was stationary, the position of tag 2 can then be calculated using basic geometry if enough additional data is also known, such as any two of the following:

Position A (e.g., using GPS)
Position B (e.g., using GPS)
Distance between A and B (e.g., using odometry)
Direction of a vector passing through A and B (e.g., compass heading).

The system described above will constrain the tag 2 position to two points symmetrically located about a line connecting A and B. To further determine which of the two possible positions is the true position of tag 2, the mobile reader can use a directional antenna, for example measuring the half plane of stronger signal strength..

Alternately, the mobile reader 3 can travel in a curved path, and use either a directional antenna or an omnidirectional antenna with multiple communication information taken at multiple positions to determine the tag 2 position.

As discussed above, the positions A or B of the tag reader 3 may be determined in a variety of ways, such as by equipping the tag reader 3 with a differential GPS that determines the latitude and longitude for the positions A and B, for example, by fixed tag readers 11 interrogating a mobile tag reader 3, by the tag reader 3 communicating with calibration tags 5, and so on.

Many of the concepts disclosed above can be enhanced by the use of directionally-sensitive communication between the tags and the tag readers. For example, by using directional antennas or antenna arrays, it is possible to improve the positioning accuracy and/or reduce the number of communications or tags required to obtain the desired positions.

The tag reader 3 may be equipped with one or more directional antennas to determine a direction from which a signal from a tag 2 is received. In an embodiment of the PinPoint Corporation Local Positioning System (LPS), each mobile tag reader 3 or

fixed tag reader 11 may support up to 16 antenna modules. Each antenna has a half power beam width (HPBW) of approximately 25 degrees on one axis, and 80 degrees on the other axis. Installing these 16 antennas in a circle, with the beam oriented vertically, results in a "pie" configuration, with each "slice" covering 22.5 degrees with some overlap. Tags 2 high overhead can be read in this configuration. Configuration details depend on the antenna design; the main goal (for the example in Fig. 2) being to use the beam pattern to distinguish between port and starboard.

Tags 2 can be configured to transmit frequently enough to be communicated with at least twice by a tag reader 3 while the tag reader 3 is in range. This approach is necessary when tag readers 3 move through a facility specifically for the purpose of inventory or "taking attendance" of tags 2 and corresponding assets. As one example, a tag reader 3 moving at 15 miles per hour covers about 22 feet per second. PinPoint LPS tags 2 are designed to "wake up" asynchronously about every 3 seconds (the factory default). In some applications, tags 2 wake up less frequently for higher system capacity and/or longer tag battery life. With some percentage of misreads and/or packet collisions, the tag reader 3 may not get at least two reads needed in some cases to determine the tag 2's position. This problem can be mitigated by combining of one or more of the following techniques:

- The tag 2's Automatic Gain Control (AGC), determines that RF or other energy in the tag reader 3's interrogation frequency is in the environment. If no such energy is detected while the tag 2 is transmitting, the tag 2 shuts down, thus saving power when no tag reader 3 is in range. Alternatively the tag 2 does not transmit any energy during this initial "test", thus further improving battery life.
- If tag reader-like RF or other energy is detected, the tag 2 transmits more frequently for a period, say once per second for 10 seconds. The tag reader energy may be coded, such as by using ON-OFF Keying (OOK), or as a beacon that can be distinguished from noise in a communication frequency band.
- When the tag reader 3 has collected enough information from a particular tag 2, it sends an on-off keyed acknowledgement (ACK) to the tag 2, thus informing the tag 2 to revert to normal mode. The tag 2 detects the on-off

signaling by monitoring the AGC. A simple form of acknowledgement is for the tag reader 3 to transmit the interrogation signal for an extra few bit periods of 19 microseconds each, such as 38 microseconds corresponding to 2 bit periods. The tag 2 detects this acknowledgement by noting the power level, and also noting a decrease in the power level at the expected time.

In an alternative design, the tags 2 transmit much less frequently, such as once per minute. A population of tag readers 3 are mounted on devices, such as forklifts 4, that move frequently among the population of tags 2. While a given forklift 4 is in range of a given tag 2, it may or may not read the tag 2. However, over a period of time, each tag 2 is seen by multiple tag readers 3 from multiple positions, and a picture of the tag 2's position is built up by combining such reads.

If it is necessary to determine asset position, i.e., tag 2 position, in 3 dimensions, antennas or antenna modules may be placed at two heights. For example, one interrogator can be positioned near ground level, while another interrogator can be mounted higher up, e.g., on a pole, with more height providing higher accuracy in the vertical direction. A distance difference between the two antennas on the vertical axis can be used to solve for height using basic geometry. A single omnidirectional antenna module can be used for this purpose.

The accuracy of a tag reader 3 to determine the position of a tag 2 is only as good as a real-time estimate of the tag reader 3's position. In addition, since the tag reader 3 may actually be moving relative to the tag 2 during communication, i.e., the tag reader 3 is at position 1 when sending an interrogation signal and at position 2 when receiving a transponded signal from the tag 2, the tag reader 3 position may be difficult to exactly determine. (In most cases, however, the slight movement of the tag reader 3 during communication with a tag 2 may be ignored as it is extremely small compared to the typical distance between the tag reader 3 and the tag 2 and/or the distance measurement errors intrinsic to the system. In this application, such slight movement has been assumed to be negligible, but in some cases it may be necessary to compensate for movement of the tag reader 3 during communication with a tag 2. Some methods such compensation are described below.) Several means are available to determine the tag reader 3's position. For example, the tag reader 3 may be associated with a GPS that provides information regarding the tag reader 3's absolute position. However, GPS

signals may not always be available, such as indoors, where GPS signals are unreliable or unavailable. When GPS is unavailable, the tag reader 3 must use different means to determine its own location. For example, the position of the tag reader 3 may also be determined and/or predicted, e.g., by using the speed and time of travel of the tag reader 3 in a known direction, by using inertial navigation systems, gyroscopes, compasses, odometers, speedometers, timers or other devices.

Fig. 3 shows another way that a tag reader 3 may determine, or obtain information sufficient to determine, the position of the tag reader 3. In the example of Fig. 3, the tag reader 3 communicates with two or more calibration tags 5. The calibration tags 5 may send information to the tag reader 3 indicating the precise position of the calibration tag 5, or the tag reader 3 or central controller 5 may store position information for each of the calibration tags 5 in the system 1 and correlate the tag 5's position with an identification number for the calibration tag 5 in a memory. The tag reader 3 may determine the distance and/or the direction at which the tag 5 lies relative to the tag reader 5 and thereby determine the position of the tag reader 3 relative to the calibration tags 5. Communication with a single calibration tag 5 may be enough to determine the precise position of the tag reader 3, or communication with multiple calibration tags 5 may be necessary, e.g., where the tag reader 3 position is determined using triangulation, signal strength, or distance measurement only techniques.

The calibration tags 5 may be embedded in the floor, walls, posts, ceiling or other structures in a facility. As one example, passive RFID tags (not requiring batteries) are buried in the floor at fixed locations, such as at the end of aisles in a warehouse. Relatively low frequency RFID tags, such as 125 KHz or 13.56 MHz, are well-suited to this purpose, do not interfere with a higher-frequency RTLS tags, and are available from a variety of vendors. Pairs of tags 5 spaced a meter or two apart may indicate, or provide information suitable to determine, direction of movement of the tag reader 3. An RFID reader in the tag reader 3 calibrates its position whenever it drives by one of these tags 5. In a warehouse, for example, tags 5 can be placed at the end of each aisle of racks. In addition to such calibration steps, various off-the-shelf technologies, such as speedometers, compasses, gyroscopes, and inertial motion sensors, may be used by the tag reader 3 or central controller 10 to estimate the position of the tag reader 3.

An alternative implementation of this concept uses RTLS tags as calibration tags 5 positioned in pre-surveyed locations. An example using 3D-iD tags and associated technology is described in connection with Fig. 4. A tag reader 3 moves along the path P1, P3, P2, P4. The tag reader 3 uses odometry and/or inertial technology, such as a speedometer combined with a compass and/or gyroscope, to measure the distance traveled and changes in direction. A calibration tag 5T1, which is in a known position, transmits when the tag reader 3 is in locations P1 and P2, resulting in distances R1 and R2 determined by the tag reader 3 or other device. If the distance between P1 and P2 is measured directly by the motion of the tag reader 3, the shape of the triangle P1-P2-5T1 can be determined. Another calibration tag 5T2 is also in the environment, and transmits when the tag reader 3 is in locations P3 and P4, resulting distances R3 and R4. Distance R3 can be used to determine the orientation of triangle P1-P2-5T1, and hence the starting point and direction of path P1-P2. Similarly, distance R2 can be used to determine the starting point and direction of triangle P3-P4-5T2. Working in this fashion, it is possible to combine readings from multiple tags 5 to track and continuously recalibrate the position of the tag reader 3. For higher accuracy, extra calibration tags 5 may be placed in the environment, allowing errors to be averaged out.

In addition, by placing some constraints on the system, it is possible to accurately determine the position of the tag reader 3 based purely on the signals of the calibration tags 5, e.g., without using inertial technology. The calibration tags 5 may be configured to transmit relatively frequently. Referring to Fig. 4, assume that calibration tags 5T1 and 5T2 are configured to transmit once per second. If the direction and speed of the tag reader 3 are assumed to be constant over a one-second period, points P1, P3, and P2, may be assumed to fall along one line, and points P3, P2, and P4 along another line.

Another approach is to configure groups of calibration tags 5 to transmit at about the same time. For example, a group of several calibration tags placed in the ceiling of a warehouse may be wired together, and be configured to transmit in rapid succession every several seconds, as illustrated in Fig. 5. Since each tag 5's datagram is about 2.5 milliseconds long, a group of ten such tags 5 can complete their transmissions in 25 milliseconds. Fig. 5 shows transmission from five tags 5 being received by the tag reader 3. Unless the tag reader 3 is moving very quickly, it will be substantially stationary during that period, as indicated by the slight motion of the tag reader 3 in the

illustration. (Note that using 3D-iD technology allows distances to be measured with an accuracy of about ±2 feet. A forklift traveling at 30 mph travels about one foot in 25 milliseconds, thus adding little to the system uncertainty.) Since the calibration tags 5 transmit every 3 seconds, a location is fixed every 3 seconds. The tag reader 3's path is estimated by interpolating between known positions.

Another approach is to assume a constrained path for the tag reader 3. For example, in a warehouse with racks, forklifts having tag readers 3 attached can be assumed to travel between racks, not through them, as shown in Fig. 6. A tag reader 3 located between Rack 2 and Rack 3 can communicate with tags 5T1, 5T2, 5T4, and 5T5. The dotted lines indicate that the communications through a rack are likely to be along an indirect path, making them somewhat longer than their actual distance. However, the communication along paths R4 and R5 will be on a direct path, and in any case are short as compared to communications from tags 5T1 and 5T2 along paths R1 and R2. Thus, the short reads from calibration tags 5T4 and 5T5 show that the tag reader 3 is located in an aisle between Rack 2 and Rack 3; and the distance measurements to calibration tags 5T4 and 5T5 indicate the tag reader 3's position in the row.

Data from the tag reader 3 can be reported to the central controller 10 by wireless means, providing an immediate data link. Alternatively, the data can be collected into the memory of the tag reader 3, and downloaded in a batch when the it returns to a base station. As noted previously, the batch link may be wireless. The central controller 10 may keep track of aisles that have been covered. If certain aisles have not been covered recently, the system software highlights this.

The use of mobile tag readers 3 may be combined with a fixed infrastructure, as discussed above. For example, on a loading dock, where trucks are continuously coming and going, a fixed RTLS infrastructure is best deployed. But if there is a large facility also where trailers are parked and/or stored, a mobile tag reader 3 can be used to take inventory periodically. The choice between the two technologies is a cost/benefit decision. On the cost side, one must consider the tradeoff between the labor needed to drive the tag reader 3 through the facility, vs. the cost of a fixed infrastructure (assuming that the tag reader 3 is moved by a human-driven vehicle - otherwise the cost of an automated mobile apparatus, such as a robot or track-guided shuttle may be considered). On the benefit side, a basic consideration is the value of current information that a fixed

infrastructure can provide. A single tag reader 3 provides an entry-level system, with additional tag readers 3 and fixed infrastructure, such as antennas 11 and so on, available as upgrades.

The present invention may determine tag-tag reader distance using methods other than signal time-of-flight. Some systems may employ signal strength as a proximity indicator. Ultra High Frequency (UHF) communications are one example of systems which can use signal strength as a measure of distance, since the electromagnetic radiation field generally weakens as a function of distance from the source of the radiation.

Several embodiments described above have focused on reading and locating 3D-iD tags from a mobile tag reader 3, and details regarding 3D-iD tags 2 and 5 are provided below. These detailed examples are not meant to be inclusive of the broad range of possible applications of the present invention, some of which were briefly mentioned above. It should be clear that other types of tags, including non-RF types and non-electromagnetic types, may also be used. The same principles may be applied to other systems, although possibly with lower performance. For example, UHF beaconing tags may be read from a mobile reader 3. Signal strength is used to very roughly determine distance from such tags to the readers. Differential GPS and/or calibration tags 5 in the environment may be used to roughly determine reader location. While the implementation is simpler and the accuracy is lower, the principles are the same.

As shown in Fig. 7, a 3D-iD asset tracking system 1 may include one or more multi-antenna module 113 cell controllers 112 that send Direct Sequence Spread Spectrum (DSSS) interrogation signals to tags 102 within range of an antenna module **113**. The tags 102 transpond this interrogation signal at low power. Information from the cell controllers 112 is sent to a central controller 110 using a TCP/IP protocol, typically via an Ethernet connection. The system 1 may also include a mobile tag reader 103 having a configuration of any of those described above, and may communicate with tags 102 in a manner similar to that described below with respect to the cell controllers 112. The mobile tag reader 103 may also communicate with the a cell controller 112 or the central controller 110. It should be understood that the antenna modules 113 may be eliminated and only mobile tag readers 3 used, if suitable.

The cell controllers 112, central controller 110 and/or the tag reader 3 can be a programmed general purpose computer, or network of programmed general purpose computers, along with other circuitry and devices required to perform the desired input/output or other functions. The controllers 110/112 or the tag reader 3 can also include other devices, such as a monitor, printer or other display device, a keyboard, user pointing device, touch screen or other user interface, storage devices, communication devices, or other electronic circuitry or components. The controllers 110/112 or the tag reader 3 can also be or include other programmed or hard-wired electronic devices, such as application-specific integrated circuits (e.g., ASICs), discrete element circuits, FPGAs, etc.

More specifically, cell controllers 112 emit a direct sequence spread spectrum interrogation signal in the 2400-2483.5 MHz ("2.45 GHz") band to tags 102. Tags 102 in range up-convert the interrogation signal's center frequency from 2442 MHz to 5800 MHz, and ensure that emissions are limited to the 5725-5875 MHz ("5.80 GHz") band. Tag 102 ID information is modulated onto the return signal, which is transmitted back to the cell controller 112 and received at low power via an antenna module 113. The cell controller 112 extracts the tag 102 ID from this return signal, and also determines the tag 102's distance from the antenna module 113 by measuring the round trip time of flight of the communication between the antenna module 113 (tag reader 3) and the tag 102. Both the interrogator and the tag 102 signal comply with current FCC Part 15 regulations, so no license is needed for operation.

In the implementation shown in Fig. 7, the cell controller 112 is attached to 4 antenna modules 113a-113d. Multiple antenna modules 113 may be used to read tag 102 distance from multiple directions, providing information to determine tag 102 position. Alternative implementations of just one antenna module 113, or 16 or more antenna modules 113, are possible.

The cell controller 112 cycles among its antenna modules 113a-113d, determining the distance between the antenna modules 113 and a given tag 102, if possible. Once the distance to three antenna modules 113 is found, the tag 102's position in space can be estimated. In many situations, it is possible to get a good estimate of tag 102 position from fewer than three antenna modules 113 and/or tag reader 3 positions.

For example, a grocery store aisle can be covered by two antenna modules 113, one at each end, and most hallways can be similarly covered.

As the tag 102 will transpond any energy received in the 2400-2483.5 MHz ISM band, a wide variety of interrogation signals might be used to read the tag 102. The commercial implementation of 3D-iD is intended to read tags 102 at maximum range and with highest position accuracy, using 127 chip sequences at a rate of 40 megachips per second. 40 megachips per second is the maximum rate supported by the 2400-2483 MHz band.

Tags 102 typically operate according to a “tag-talks-first” paradigm. Tags 102 may wake up spontaneously, transmit their unique codes, and then go back to sleep. Each transmission is short, on the order of 2.5 milliseconds. The sleep time can vary based on application requirements. For example, tags 102 attached to personnel might transmit every two seconds, while tags 102 attached to inventory might be set to transmit once per minute.

The tag data protocol includes a capability to pass along information provided by a closely integrated device. For example, a specialized tag 102 integrated with a temperature sensor can be used to report current and historical environmental data. As another example, personnel tags 102 include a “call button”. To support such low-bandwidth communication, the data protocol may include bandwidth to uplink a small amount of status information.

The tag 102 receives a DSSS signal from the interrogator, centered at 2442 MHz or another frequency in the 2400-2483 MHz band, at a receive antenna 1021. This signal is first filtered by a filter 1022 and amplified by an amplifier 1023. The signal is then modulated by a modulator 1024 that either passes the signal unchanged, or inverts the phase by 180°. The modulator 1024 operates under microprocessor 1025 control. The modulated signal is then filtered by a filter 1026, amplified by an amplifier 1027, and then mixed at a mixer 1028 with the output of a 3358 MHz oscillator 1029, resulting in a signal of 2442+3358=5800 GHz. This 5800 GHz response is then filtered by a filter 1030, amplified by an amplifier 1031, filtered again by a filter 1032, and transmitted though an antenna structure 1033. An Automatic Gain Control (AGC) 1034 keeps the operation of tag components in an optimal range. Tag operation is controlled by the microprocessor 1025, such as a PIC processor from Microchip.

3. To pick the best antenna for collecting the rest of the datagram.

The tag preamble 81 includes a constant bit pattern of 38 effective one bits. A one bit is defined as having no phase change, so the preamble 81 has a constant phase. The preamble 81 includes 31 bits for determination of distances from each of up to 16 antennas, and 7 bits to allow for cell controller 112/tag reader 3 overhead. If fewer than 16 antennas are connected and/or supported, the cell controller 112/tag reader 3 can reduce its duty cycle accordingly with minimal impact on performance.

End preamble 82 allows the cell controller 112/tag reader 3 to synchronize its baseband clock. The end preamble 82 begins by the tag 102 shutting down its transmitter for 6 microseconds. The rest of the first bit interval, and the remaining 3 bits allows the interrogator to reacquire the tag signal. This field is optional, and improves reliability in certain interrogator designs.

The start data sequence flag 83 includes a "010" bit pattern to indicate end-of-preamble. The tag version field 84 follows the start data sequence 83 and includes 4 bits that may be used to support future enhancements to the protocol and to provide a signal for future interrogators to enable backward compatibility. In this version of the protocol, its value is "0000".

The tag serial number 85 follows the tag version 84 and includes 32 bits organized as four bytes (msb). There is no special meaning to the 4 bytes other than the tag serial number 85.

The tag status or housekeeping field 86 follows the tag identification 85 and includes 8 bits that may be used for fixed housekeeping purposes. The 8 bits are UUUUUUTB (msb), where B=1 indicates low battery and T=1 is a tamper indicator. For personnel tags 102, the tamper detect bit may be used to indicate use of a call button. The six remaining bits are left unspecified, and are intended for application-specific uses.

The tag data field 87 follows the status field 86, and includes 24 bits whose function varies by application. A typical application is to report the status of an environmental sensor, or to report status information from tagged equipment.

The next to last field is a CRC 88. The CCITT 16-bit CRC 88 takes as input: the version, serial number, status and data fields.

Note that the DSSS signal is not demodulated by the tag 102; it is simply passed through. This provides the system with the performance of a DSSS system without the necessity of a DSSS modulator or demodulator on the tag 102. In enhanced implementations of this design, an Rx Threshold Detector may be added to the receiver, providing support for an on-off keyed (OOK) forward link.

Fig. 7 is intended to clarify the transponding and modulation operations that might occur in the RFID tag 102. No implementation recommendation or constraint is intended with regard to nature and placement of components, and the modulation result may be made consistent with the description above and the specifications in Appendix A.

The RFID tag 102 normally performs two basic functions.

- It provides a RF mirror (frequency translation) so the interrogator can locate it.
- It modulates the interrogator signal to transmit the tag information back to the interrogator using a tag protocol.

The tag 102 spends most of its time in the sleep state. During its active interval the tag 102 "wakes up" by stabilizing its internal oscillators, calculating a Cyclic Redundancy Check (CRC), initiating radio transmission and modulation, sending its datagram and finally returning to the sleep state.

Fig. 8 shows an example of a tag datagram used by the tag 102 shown in Fig. 7 having nine contiguous sections. The sections are the tag preamble 81, the end preamble 82 (optional), the start data sequence 83, the datagram version identifier 84, the tag serial number 85, the status bits 86, the tag data 87, the CRC 88, and end bit 89. This datagram may be sent once during the tag 102 RF-on cycle. Each individual bit may span a 19.05 microsecond period, corresponding to an interrogator signal of six 127-chip sequences at a rate of 40 megachips per second.

The tag preamble 81 may used by the interrogator (cell controller 112 or tag reader 3) to perform three functions:

1. To search for the tag 102 sequentially through each of the interrogator's antennas. If a tag 102 is seen in this search process, the interrogator then proceeds with the subsequent steps;
2. To determine the distance to the tag 102 from each antenna that sees the tag;

The final field is used as a stop bit 89, which may be a replication of the last bit in the checksum field and allows for a smooth and controlled end of acquisition within the interrogator and graceful tag shutdown. It is also possible for enhanced tags 102 to receive on-off keyed (OOK) messages from the interrogator immediately following the end of the datagram, for purposes such as acknowledgements, changes in tag parameters (such as sleep times), or commands to devices attached to the tags 102.

Each bit of the tag datagram may last for 19.05 microseconds and there are effectively 126 bits in a datagram (excluding the optional end premable 82), so the datagram may last for about 2.4 milliseconds.

At the end of a tag transmission, the tag 102 may go to sleep for an amount of time pre-programmed into its microprocessor 1025. A typical three second sleep time provides about a 1000:1 duty cycle. It is desirable to include a randomized component in the sleep cycle to prevent pairs of tags 102 from transmitting in a repeated synchronized fashion. The randomization function may vary according to the implementation of the sleep cycle. A randomization formula that varies as a function of tag ID is recommended. This is an average, accounting for randomization.

While the invention has been described in conjunction with specific embodiments thereof, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art. Accordingly, embodiments of the invention as set forth herein are intended to be illustrative, not limiting. Various changes may be made without departing from the invention.

Appendix A

Forward Link Parameters

Parameter Number	**Parameter Name**	**Description**
F 1	Operating Frequency Range	2400-2483.5 MHz
F 1a	Default Operating Frequency	2442 MHz (center frequency)
F 1b	Operating Channels	2442 MHz only (Center Frequency)
F 1c	Operating Frequency Accuracy	± 25 ppm maximum.
F 1d	Frequency Hop Rate	Not applicable
F 1e	Frequency Hop Sequence	Not applicable
F 2	Occupied Channel Bandwidth	The 20 dB bandwidth is regulated by FCC Part 15, Section 15.247
F 3	Interrogator Transmit Maximum EIRP	The maximum EIRP transmitted by the interrogator antenna is regulated by reference document FCC Part 15, Section 15.247. This maximum is 30 dBm output from the interrogator and 36 dBm EIRP from the interrogator transmit antenna.
F 4a	Interrogator Transmit Spurious Emissions, In-Band	Not applicable.
F 4b	Interrogator Transmit Spurious Emissions, Out-of-Band	The interrogator shall transmit in conformance with spurious emissions requirements defined in reference FCC Part 15, Sections 15.205 and 15.209.
F 5	Interrogator Transmitter Spectrum Mask	The interrogator transmitter spectrum mask is regulated by reference document FCC Part 15, Section 15.247. The peak power spectral density conducted from the intentional radiator to the antenna shall not be greater than 8 dBm in any 3 kHz band during any time interval of continuous transmission.
F 5a	Transmit to Receive Turn Around Time	Not applicable.
F 5b	Receive to Transmit Turn Around Time	Not applicable.
F 5c	Interrogator Transmit Power On Ramp	Not applicable.
F 5d	Interrogator Transmit Power Down Ramp	Not applicable.
F 6	Modulation	DSSS MPSK (BPSK or higher)

Parameter Number	**Parameter Name**	**Description**
F 6a	Spreading Sequence	Implementation-specific combination of the following 127-chip sequences:03,FA,A6,77,4B,1B,DA,D9,23,85,F2,B9,A2,78,A1,8302,4D,3D,C3,F8,EC,52,FA,A1,6F,39,59,83,6B,A3,2303,36,39,D7,09,82,AD,25,3C,8D,43,FB,B7,A2,CB,E302,C1,D0,9C,69,2E,DC,D9,5A,FB,C3,11,4C,F5,47,F303,09,3F,BE,3A,A5,7A,67,35,88,BB,21,E5,B8,28,DB03,A8,B8,F7,6B,FA,61,A1,4B,65,58,82,7C,E4,8C,DF02,86,C8,3C,5A,C2,27,7A,33,4C,72,AE,A4,BF,9F,6F02,B7,F3,6A,89,33,C7,75,E9,65,39,18,B8,43,41,F703,5D,2A,DC,84,49,EA,0B,CE,FE,CB,19,B4,7C,38,A7
F 6b	Chip Rate	40 megachip/sec
F 6c	Chip Rate Accuracy	Not critical.
F 6d	On-Off Ratio	Not applicable.
F 6e	Duty Cycle	Not applicable
F 6f	FM Deviation	Not applicable.
F 7	Data Coding	Not applicable (read-only)
F 8	Bit Rate	315 kbps
F 8a	Bit Rate Accuracy	Not critical.
F 9	Interrogator Transmit Modulation Accuracy	Not restricted.
F 10	Tag Receiver Non-Destructive Input RF Level	Tag must be able to withstand power delivered from a 1000 mW interrogator at 0.5 meters, or from a 100 mW interrogator at any distance.
F 11	Preamble	Not applicable.
F 11a	Bit Sync Sequence	Not applicable.
F 11b	Frame Sync Sequence	Not applicable.
F 12	Scrambling	Not applicable.
F 13	Bit Transmission Order	Not applicable

Return Link Parameters

Parameter Number	**Parameter Name**	**Description**
R 1	Operating Frequency Range	5725-5875 MHz
R 1a	Default Operating Frequency	5800 MHz (center)
R 1b	Operating Channels	Frequency shifting transponder: 2400-2484 to 5758-5842
R 1c	Operating Frequency Accuracy	Up-conversion accomplished using 3358 MHz oscillator, ±35 ppm.
R 1d	Frequency Hop Rate	Not applicable.

Parameter Number	Parameter Name	Description
R 1e	Frequency Hop Sequence	Not applicable.
R 2	Occupied Channel Bandwidth	Up-converted and low-power approximate replica of 2400-2484 spectrum. Matches Interrogator spectral profile in normal operation.
R 3	Transmit Maximum EIRP	The maximum EIRP transmitted by the tag antenna is regulated by reference document FCC Part 15, Section 15.249. This maximum is 50 millivolts/meter measured at a distance of 3 meters. Field strength limits are based on average limits. However, the peak field strength of any emission shall not exceed the maximum permitted average limits by more than 20 dB under any condition of modulation.
R 4a	Transmit Spurious Emissions, In-Band	Not applicable.
R 4b	Transmit Spurious Emissions, Out-of-Band	The tag shall transmit in conformance with spurious emissions requirements defined in reference document FCC Part 15, Section 15.249. Emissions radiated outside of the 5725-5875 MHz frequency band, except for harmonics, shall be attenuated by at least 50 dB below the level of the fundamental or to the general radiated emission limits in §15.209, whichever is the lesser attenuation. Harmonics are limited to 500 microvolts/meter.
R5	Transmit Spectrum Mask	Transponder; not applicable.
R 5a	Transmit to Receive Turn Around Time	Not applicable.
R 5b	Receive to Transmit Turn Around Time	Not applicable.
R 5c	Transmit Power On Ramp	Radio shall be disabled until power on ramp completed.
R 5d	Transmit Power Down Ramp	Radio shall be disabled prior to power down ramp.
R 6	Modulation	DBPSK.
R 6a	Sub-carrier Frequency	3358 MHz (as defined in standard)
R 6b	Sub-carrier Frequency Accuracy	Not applicable
R 6c	Sub-Carrier Modulation	Not applicable
R 7	Data Coding	Phase change of 0 represents 1; phase change of represents 0.

Parameter Number	**Parameter Name**	**Description**
R 7a	Spreading Sequence	Not applicable; transponder.
R 7b	Chip Rate	Not applicable; transponder.
R 7c	Chip Rate Accuracy	Not applicable; transponder.
R 6d	On-Off Ratio	Not applicable.
R 6e	Duty Cycle	Not applicable.
R 6f	FM Deviation	Not applicable.
R 8	Bit Rate	1 bit per 19.05 microseconds.
R 8a	Bit Rate Accuracy	±10,000 ppm
R 9	Tag Transmit Modulation Accuracy	10°
R 10	Data Coding	Data Coding is specified in the system description.
R 11	Scrambling	None.
R 12	Bit Transmission Order	MSB

CLAIMS

1. A positioning system, comprising:

a tag, adapted for coupling to an asset, having an unknown tag position; and

a tag reader, adapted to be coupled to a mobile apparatus while in operation, having a tag reader instantaneous position;

wherein the tag reader is adapted to generate information suitable for determination of a distance between the tag position and the tag reader instantaneous position; and

wherein the information is a time-of-flight of a signal traveling between the tag and the tag reader.

2. The system of claim 1, wherein the signal is at least one of: traveling from the tag to the tag reader, traveling from the tag reader to the tag, and traveling round-trip between the tag and the tag reader.

3. The system of claim 1, wherein at least one of the tag and the tag reader may transpond the signal.

4. A positioning system, comprising:

a tag, adapted for coupling to an asset, having an unknown tag position; and

a tag reader, adapted to be coupled to a mobile apparatus while in operation, having a tag reader position;

wherein the tag reader is adapted to generate information suitable for determination of a distance between the tag position and the tag reader position; and

wherein said information is a signal strength of a communication between the tag and the tag reader indicating proximity of the tag to the tag reader; and

wherein an estimate of the tag position, based on the information from the tag reader, is available on a central controller that is not co-located with the tag reader.

5. A positioning system, comprising:

a tag, adapted for coupling to an asset, having an unknown tag position; and

a tag reader, adapted to be coupled to a mobile apparatus while in operation, having a tag reader instantaneous absolute position;

wherein the tag reader is adapted to generate information suitable for determination of a distance between the tag and the tag reader based on communication between the tag and the tag reader, corresponding to a single tag reader instantaneous absolute position; and

wherein the absolute position of the tag reader is known.

6. The system of claim 3, wherein the determination of the distance between the tag position and the tag reader position is determined using a travel time-of-flight of communication information traveling between the tag and the tag reader.

7. The system of any of claims 1, 2, or 3, wherein the tag is an RFID tag.

8. The system of any of claims 1, 2, or 3, wherein said tag reader is adapted to generate information suitable for determination of the position of the tag based on communication between the tag reader and the tag and a known position of the tag reader.

9. The system of any of claims 1, 2, or 3, wherein the tag reader can move in any direction while in operation.

10. The system of any of claims 1, 2, or 3, wherein the tag reader determines a position of the tag relative to a tag reader position based on at least two communications between the tag and the tag reader, each of the at least two communications being performed while the tag reader is at a corresponding discrete position relative to the tag and used to determine at least two distances between the tag reader and the tag.

11. The system of any of claims 1, 2, or 3, wherein an absolute position of the tag is determined based on distance and direction information obtained by the tag reader from communication with the tag.

12. The system of any of claims 1, 2, or 3, wherein an absolute position of the tag reader is determined using at least one of: a global positioning system (GPS), inertial navigation data, odometry, speed and compass headings, and a communication with a calibration tag.

13. The system of any of claims 1, 2, or 3, wherein the tag reader is coupled to a mobile apparatus, wherein the mobile apparatus is one of: a truck, a forklift, an automobile, a marine vessel, an aircraft, a conveyor system, an elevator, a shipping container, a postal package, an article of cargo, a robot, an animal, and a human.

14. The system of any of claims 1, 2, or 3, wherein the tag is attached to an asset, and the tag reader is attached to a mobile apparatus.

15. The system of any of claims 1, 2, or 3, further comprising at least one calibration tag that is fixed in a known absolute calibration tag position and communicates with the tag reader to allow determination of an absolute tag reader position relative to a fixed reference point.

16. A positioning system, comprising:

a plurality of RFID tags, each tag being in a fixed, known RFID tag position; and

a RFID tag reader, adapted to be coupled to a mobile apparatus while in operation, having a RFID tag reader instantaneous absolute position;

wherein the RFID tag reader is adapted to generate information suitable for determination of the distance between the RFID tag reader position and a fixed, known RFID tag position based on communication between the RFID tag and the RFID tag reader, corresponding to a single RFID tag reader instantaneous absolute position.

17. The system of claim 16, wherein the tag reader determines the distance between the RFID tag reader position and an RFID tag using a travel time-of-flight of communication information traveling between at least one RFID tag and the RFID tag reader.

18. The system of claim 16, wherein the RFID tag reader determines a position of the RFID tag reader relative to the RFID tag position based on at least two communications between the RFID tag and the RFID tag reader while the RFID tag reader is at least at two distinct positions relative to the RFID tag.

19. The system of claim 16, wherein a RFID tag transmits data containing the fixed RFID tag position.

20. The system of claim 16, further comprising a central controller that determines the RFID tag reader position.

21. The system of claim 16, further comprising a plurality of movable asset tags that are associated with assets and have an undetermined asset tag position, and

wherein the RFID tag reader generates information suitable for determining an absolute position of an asset tag based on communication with the asset tag.

22. A method for tracking assets, comprising:

providing a tag, associated with an asset, at an unknown tag absolute position;

providing a tag reader adapted to be coupled to a mobile apparatus having a known tag reader absolute position;

receiving a signal from the tag;

determining a distance between the tag position and the tag reader absolute position based only on communication between the mobile tag reader and the tag; and

estimating the tag absolute position based on the distance between the tag and the tag reader and knowledge of the tag reader absolute position.

23. A method for tracking assets, comprising:

providing a tag, associated with an asset, at an undetermined tag position;

providing a tag reader adapted to be coupled to a mobile apparatus;

receiving a signal from the tag;

determining a first distance between the undetermined tag position and the tag reader at a first tag reader position based only on a single communication between the mobile tag reader and the tag; and

determining a second distance between the undetermined tag position and the tag reader at a second tag reader position based on communication between the tag and the reader corresponding to a single tag reader position; and

determining the tag position based on the first distance and the second distance and knowledge of the first and second tag reader positions.

24. The method of any of claims 22 and 23, wherein the step of providing a tag reader adapted to be coupled to a mobile apparatus to comprises providing a freely-mobile apparatus, capable of moving in any direction.

25. The method of any of claims 22 and 23, further comprising:

providing a plurality of calibration tags at fixed, known positions; and

determining the absolute position of the tag reader based on communication between the calibration tags and the tag reader.